Phase Diagram and Instability of Dense Neutral Quark Matter

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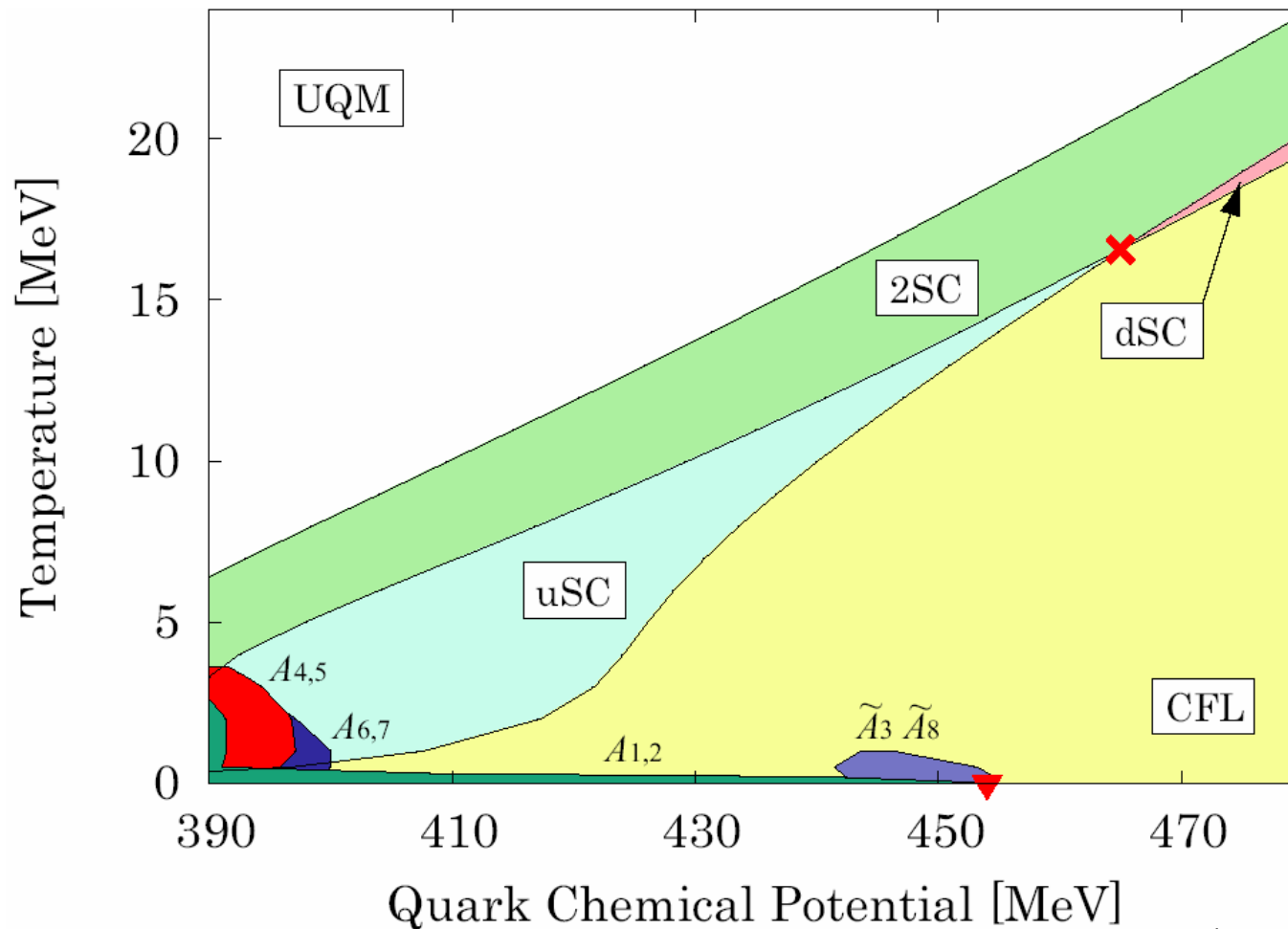
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Phase Diagram at High Density

hep-ph/0510299

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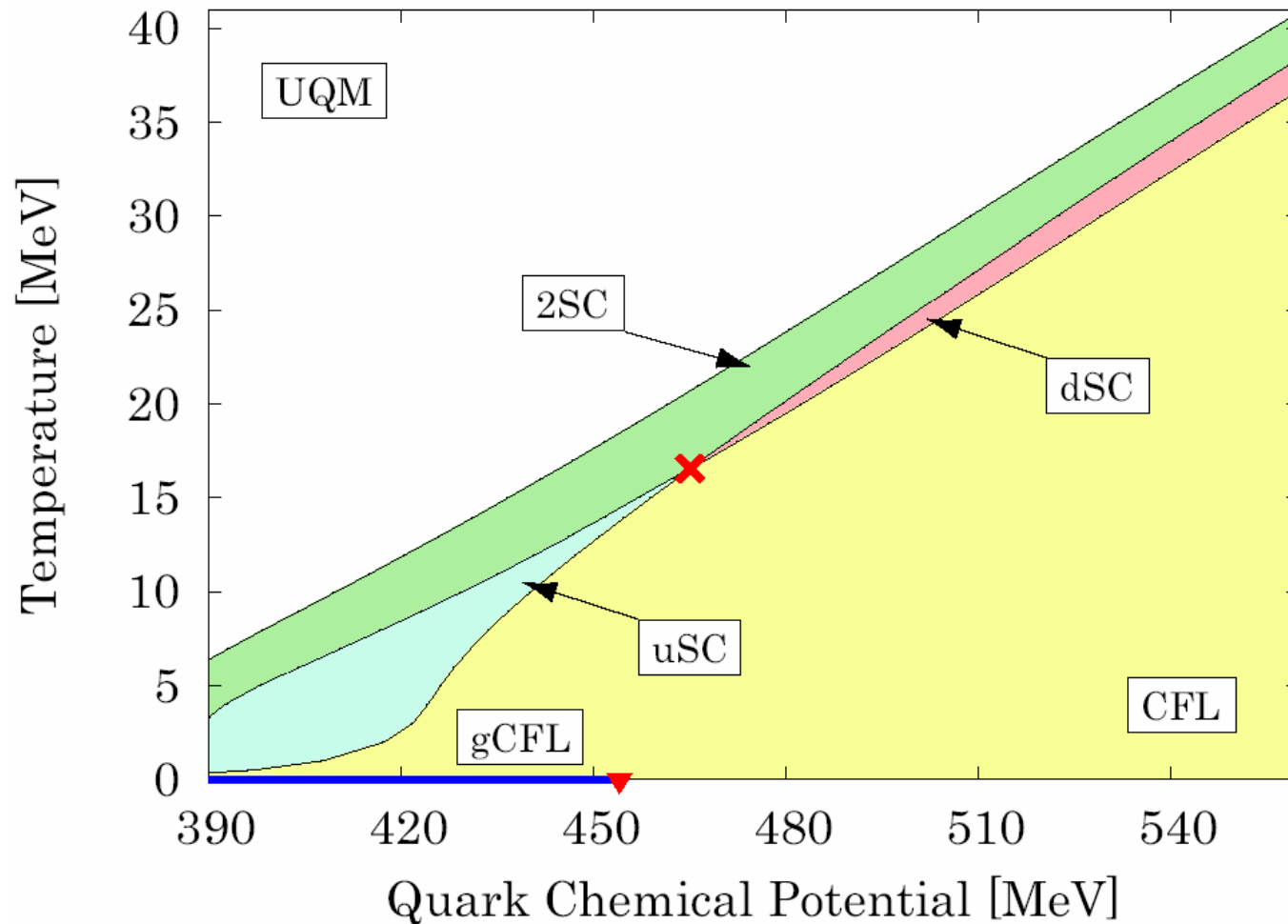
Our Goal --- Instability

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Cooper Pairing Patterns

Diquark Condensate

$$\Delta_{\alpha i} \propto \varepsilon_{\alpha\beta\gamma}\, \varepsilon_{ijk} \left\langle \overline{\psi}_{\beta j}\, \mathrm{i}\gamma_5 C\, \overline{\psi}_{\gamma k}^{\mathrm{T}} \right\rangle$$

Anti-symmetric in Color (attractive in OGE)
Anti-symmetric in Flavor, Positive Parity (energetically)
Anti-symmetric in Spin

Color-Flavor Locking $\Delta_{\alpha i} = \delta_{\alpha i}\Delta_i$ analogous to the ^{3}He B phase

$$\Delta_{bs} \to \Delta_3 \qquad\qquad \Delta_{ru} \to \Delta_1 \qquad\qquad \Delta_{gd} \to \Delta_2$$

$$
\begin{array}{ccc}
ru\text{-}gd & gd\text{-}bs & bs\text{-}ru \\
gu\text{-}rd & bd\text{-}gs & rs\text{-}bu
\end{array}
$$

Family of Color Superconductors

$\Delta_1, \Delta_2, \Delta_3 \neq 0 \quad$ Color - Flavor Locked (CFL) Phase

$$\Delta_1 = 0, \quad \Delta_2, \Delta_3 \neq 0 \qquad \text{uSC}$$

$$\Delta_2 = 0, \quad \Delta_1, \Delta_3 \neq 0 \qquad \text{dSC}$$

$$\Delta_1 = \Delta_2 = 0, \quad \Delta_3 \neq 0 \qquad \text{2SC}$$

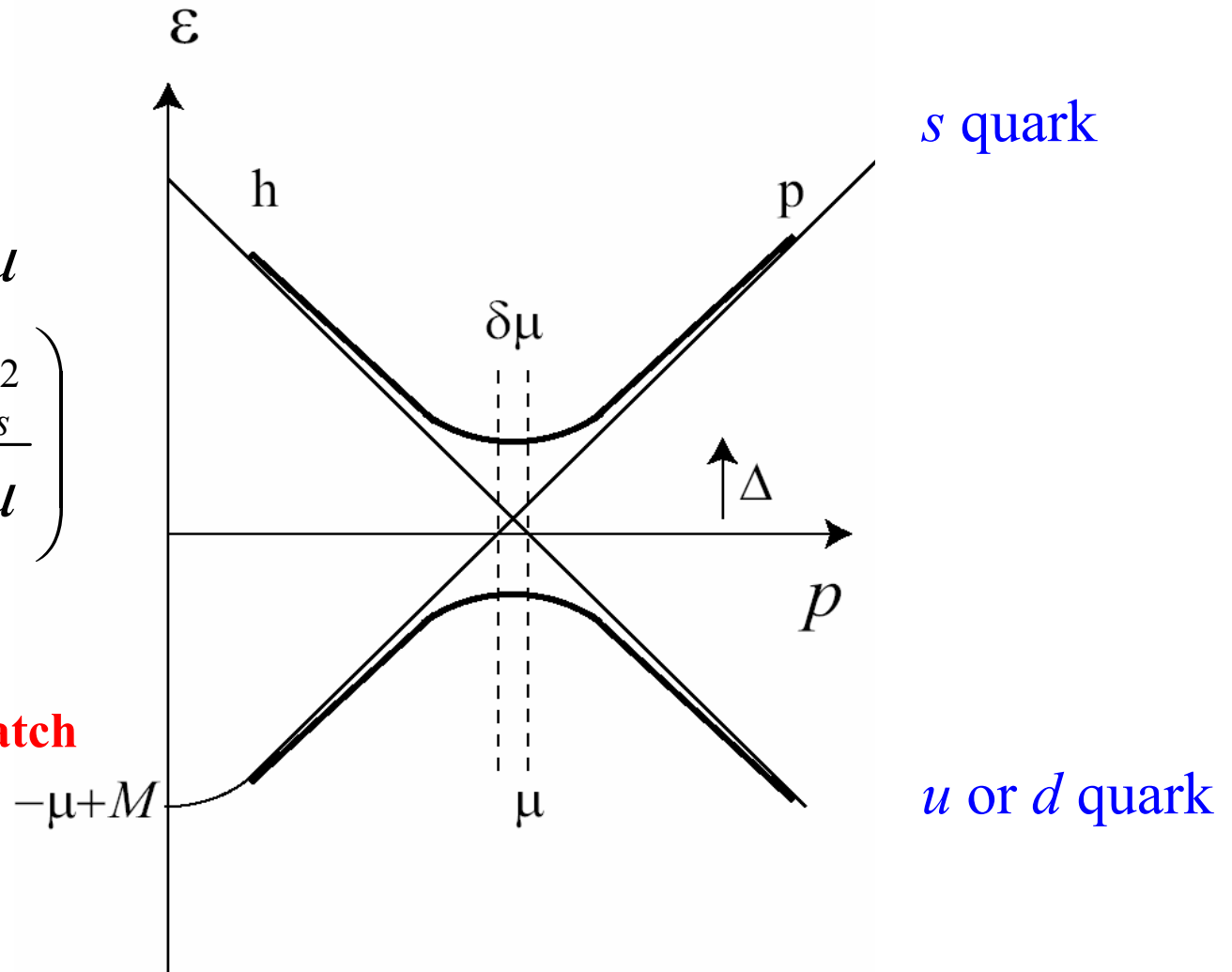$$\Delta_1 = \Delta_2 = \Delta_3 = 0 \qquad \text{UQM}$$

Effect of Non-Zero M_s

$M_s \neq 0$

$$\sqrt{p^2 + M_s^2} - \mu$$

$$\approx p - \left(\mu - \frac{M_s^2}{2\mu} \right)$$

Fermi Surface Mismatch

ε

s quark

h

p

$\delta\mu$

$\uparrow\Delta$

p

$-\mu+M$

μ

u or *d* quark

Gapless Superconductor

Gapless dispersion appears when

$$\Delta < \delta\mu / 2$$

CFL

⬇

gapless CFL (gCFL)

This happens for Δ_1 pairing, which makes Δ_1 disfavored.

$$\Delta_1 < \Delta_2 < \Delta_3$$
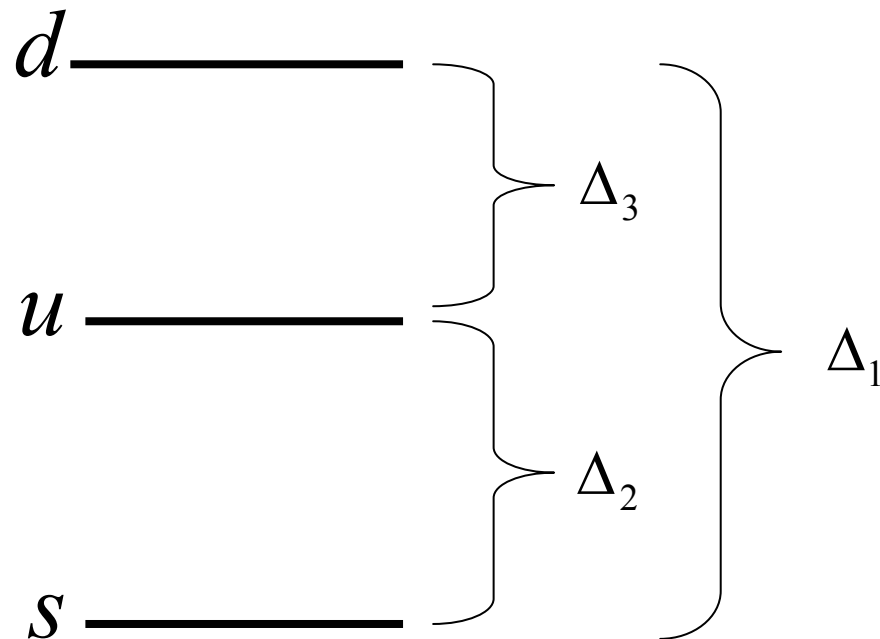
Δ_1 melts first ➔ uSC
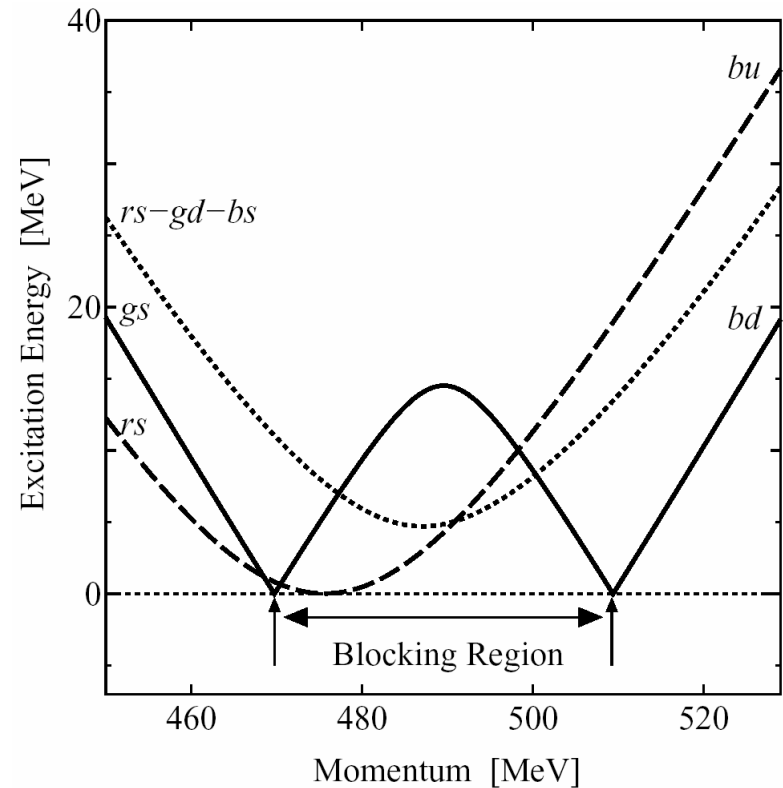
bd-gs (Δ_1)   gapless
rs-bu (Δ_2)   gapless (quadratic)

dSC near Tc

Electric neutrality with $M_S \neq 0$

$$Q_e = \mathrm{diag}\left(\tfrac{2e}{3}, -\tfrac{e}{3}, -\tfrac{e}{3}\right)$$

d ──────── $\left.\vphantom{\begin{array}{c}a\\b\\c\end{array}}\right\}\Delta_3$

u ──────── $\left.\vphantom{\begin{array}{c}a\\b\\c\end{array}}\right\}\Delta_1$

$\Delta_2 < \Delta_1 < \Delta_3$

s ──────── $\left.\vphantom{\begin{array}{c}a\\b\\c\end{array}}\right\}\Delta_2$

Δ_2 vanishes first ➔ dSC

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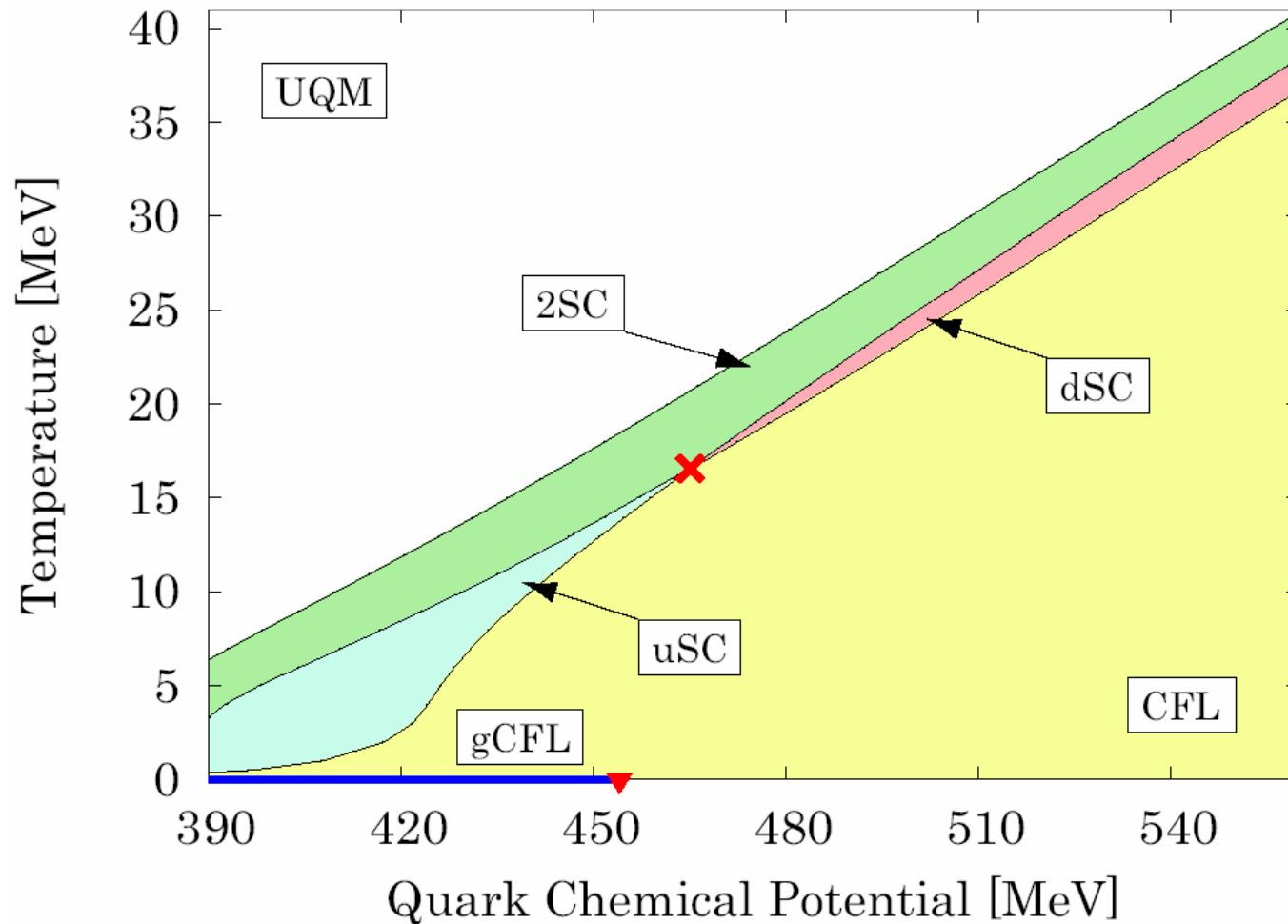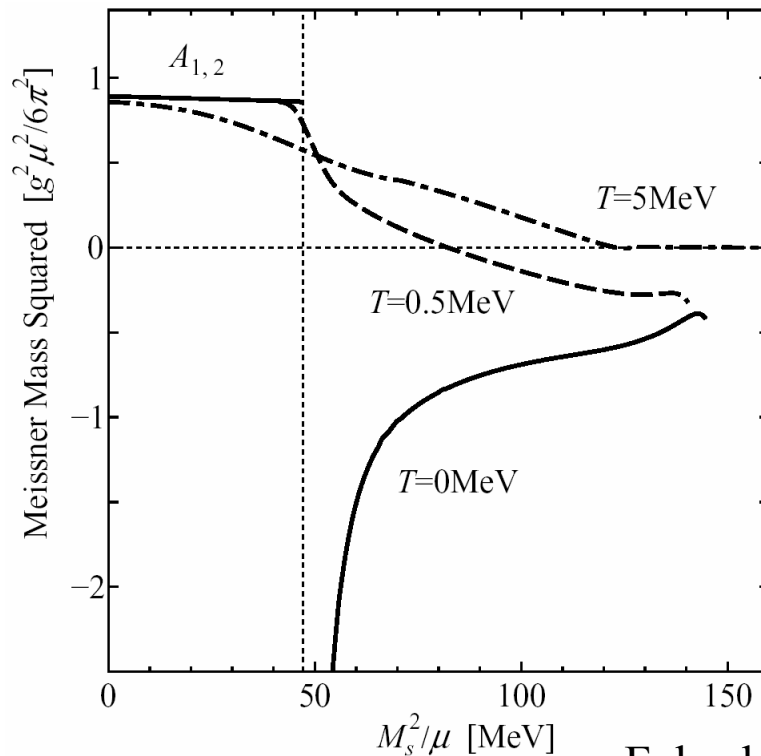
Chromomagnetic Instability

■ Meissner Screening Mass

Meissner mass is the screening mass for the transverse gluons.

Meissner mass is imaginary
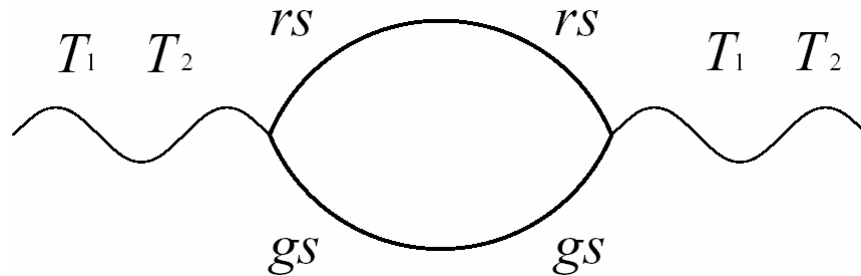in the gapless phases
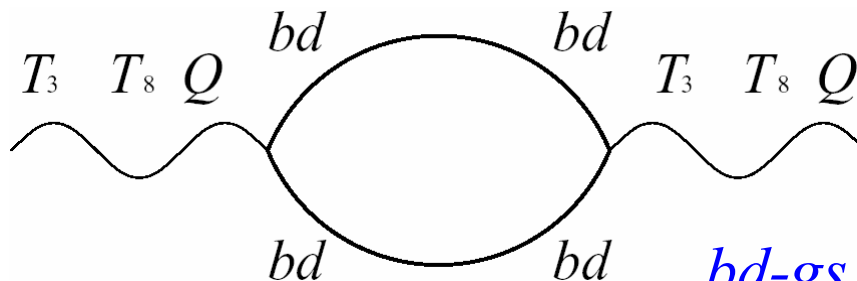
Shovkovy-Huang

Gapless Quarks

near the gCFL onset

Fukushima, PRD72 : 074002 (2005)

Unstable Gluons near gCFL

$A_{1,2}$ gluons λ_1 in color space $\rightarrow$ red-green

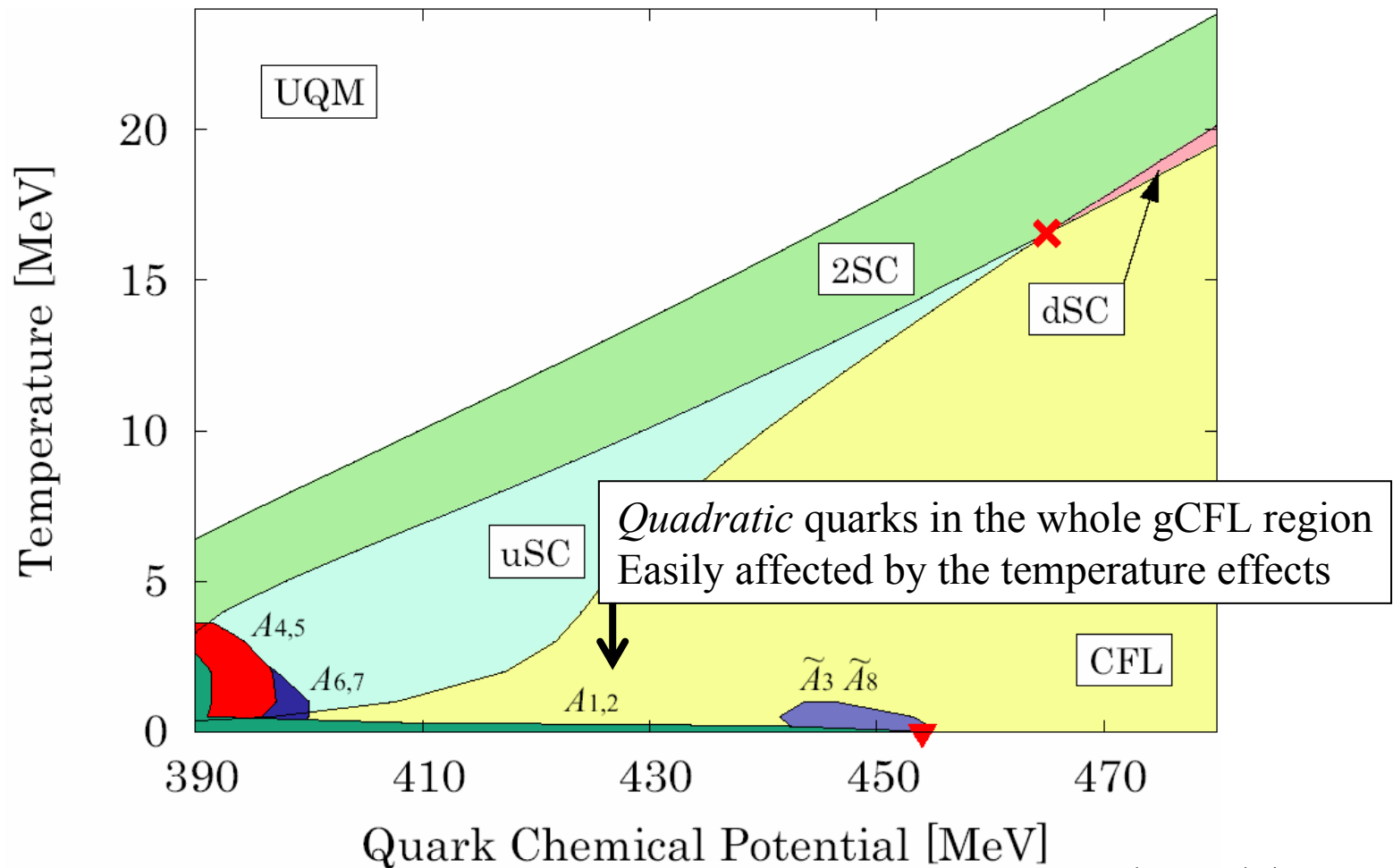$A_{3,8}$ gluons (photon)   same colors

bd-gs (Δ_1)   gapless
rs-bu (Δ_2)   gapless (quadratic)

Instability Regions

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Colored Crystalline Phase

Instability for A_i = Instability for q_i (Giannakis-Ren)

$$\langle \psi\psi \rangle \sim |\Delta| e^{iq\cdot x}$$ Crystalline Superconducting Phase

(Covariant Derivative $q_i + A_i$)

Five variational parameters are needed

$$A_{1,2} \quad A_{4,5} \quad A_{6,7} \quad A_3 \quad A_8$$

Rotational symmetry is broken

Calculations are *technically* very difficult.

Summary

- The QCD phase diagram in the high density region has the CFL, uSC, dSC phases.
  - □ uSC comes out as a remnant of the gCFL phase.
  - □ dSC results from the Fermi surface ordering.

- The chromomagnetic instability occurs for $A_{1,2}$ and $A_{3,8}$ near the gCFL onset.
  - □ Quadratic quarks cause the instability.
  - □ Colored Crystalline Phase…How?